Norges miljø- og
biovitenskapelige
universitet

Master's Thesis 2018 60 ECTS

Faculty of Environmental Sciences and Natural Resource Management

How do different shot types perform under hunting conditions? An examination of data from the Norwegian Hunters and Anglers Associations' Test hunter project

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Master Thesis in Natural Resource Management

May 2018

Preface

This thesis is written as the final work of my masters' degree at the Norwegian University of Life Sciences.

I especially want to thank my helpful and committed supervisor Leif Egil Loe at NMBU for his guidance and patience through the entire process. I also want to give a big thank you to Hege Gundersen at NINA for her help with understanding the data set and helpful comments during the process.

Several people deserve have helped me in the search for information on the subject of shotshell performance: Thank you to Bjørn Ivar Rindal who helped with interpreting the data set, thank you to Jean-Yves Mondain Mondval for helpful comments and copies of your work, and thank you to Tom Roster for your articles that were not available elsewhere. I also want to give a special thank you to our faculty librarian Atle Hårklau, and my in-house librarian Eir Mariann Hvidsten, for your invaluable help in locating old obscure research articles and reports which are difficult to find.

Norwegian University of Life Sciences

Ås, 14.05.2018

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Abstract

The possible effects of replacing lead shot with alternative shot types in shotgun ammunition is an ongoing debate in many countries. Varying restrictions on lead shot use have existed in Norway since 1991, and the recent EU-proposition for new restrictions on the use of lead shot in wetlands opens for yet another revision of these regulations. In light of the possible new regulations it is interesting to re-examine the data on shot shell performance gathered by hunters under field conditions during the NJFF Test hunter project.

The purpose of this study is to explore how the different shot types and pellet sizes differ in their killing efficiency, and give recommendations on choice of pellet size and maximum shooting distance for each shot type.

Data was gathered under field conditions over three hunting seasons, by approximately 100 experienced hunters selected by the Norwegian Association of Hunters and Anglers in the associations own Test hunter project. The hunters recorded species, shooting distance and angle, ammunition characteristics and outcome of each hunting situation that resulted in hits on game. Rock ptarmigan and willow ptarmigan were the only species represented with enough observations (n=2436) in the collected data to give robust model predictions for a wider selection of shot types and pellet sizes. Bagging probability and light hit probability were modeled using mixed generalized additive models (GAMM). Pellet size, shot angle and distance were fitted as fixed factors and hunter identity as a random intercept. Separate models were fitted for each shot type due to strong imbalance between shot type and pellet size.

Analysis of hunters' bagging success showed differences between shot types and pellet sizes. Within the tested interval of 15 to 35 meter (normal shot gun range), increased distance had a negative effect on predicted probability of bagging birds with steel shot, but no clear drop in efficiency of lead or bismuth shot. The smallest steel shot (US size 6) showed the largest drop in predicted bagging success, from 95% at 15m, to 71% at 35m. The largest steel shot (US size 2) only dropped from 99% to 95% over the same range, and showed similar performance to lead and bismuth shot. All tested pellet sizes of lead and bismuth showed predicted probability of bagging hit birds to be in the 90% to 100% range. Results from analysis of light hit probabilities were largely inverse to bagging probabilities, with the exception that the largest steel shot showed an increased probability of causing light hits over lead and bismuth shot.

In conclusion, this study indicates that switching from lead to steel shot might cause an

increase in animal suffering, as rates of light hits differ between lead and steel shot. However, the study shows that bag rates will not necessarily change with a switch from lead to alternative shot. If hunters use bismuth shot or the correct pellet size of steel shot, bag rates will not be affected by replacing lead with the tested non-toxic alternatives.

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1 Introduction

Lead poisoning of waterfowl caused by ingestion of spent lead shot has been a concern for wildlife management over a century (Jordan & Bellrose, 1951). In areas of high hunting intensity, shotgun pellets can collect together with gravel in wetland sediments and on terrestrial surfaces. These pellets are then ingested together with the gravel birds pick up for digestion (Bellrose, 1959; Szymczak, 1978). Predators are exposed to lead by consuming prey with increased levels of lead in body tissue, and from consuming crippled or dead un-retrieved game containing lead shotgun pellets. These poisoning mechanisms have been shown to affect several species on both the European and American continent (Bellrose, 1959; Locke & Friend, 1992; Mudge, 1983; Pain et al., 2009). Solutions to the lead poisoning issue have been sought for many decades, and the accepted solution today is a switch from lead shot to non-toxic shot for hunting (Mudge, 1992). As a consequence of this, many countries worldwide have introduced bans on lead shot. The bans vary, from bans on the use of lead shot over wetlands, to total bans on lead shot for both hunting, practice and competition shooting (Avery & Watson, 2008).

A lot of controversy exists around the mandatory use of non-toxic shot. Many hunters, NGO's and ammunition manufacturers question the validity of the reasons for banning lead shot, and express their concerns over the possible consequences as shooters and hunters switch to non-toxic shot. Among the most commonly expressed concerns are: increased wear on gun barrels and chokes, safety with hard shot in older guns, ricochet danger from hard shot, higher price and reduced availability of cartridges suitable for necessary practice, and perhaps most importantly, the concern of increased animal suffering and an increased rate of un-retrieved crippled game when hunters are forced to give up lead shot (Hebert et al., 1984; Humburg et al., 1982; Shedden, 1992; Smith & Townsend, 1981).

If a switch to non-toxic shot types increase rates of game crippled and un-retrieved by hunters, this may result in increased population mortality in the hunted species. Knowledge of changes in mortality factors will be of importance for wildlife management, as these rates affect how many birds may be harvested during the hunting season (Morehouse, 1992; Sanderson & Bellrose, 1986). This has motivated investigation of the killing efficiency of both lead shot and the various non-toxic replacements. Tests have been performed under laboratory conditions and controlled field conditions, and some tests have included necropsy analysis of wounded or dead birds. The studies have been done on species of varying sizes. Variation has spanned from the little mourning dove *(Zenaida macroura)* (Pierce et al., 2015), through several species of wild ducks and game farm mallards *(Anas platyrhynchos)* (Andrews & Longcore, 1969; Hebert et al., 1984; Humburg et al., 1982; Kozicky & Madson, 1973; Nicklaus, 1976), released pheasants *(Phasianus colchicus)* ((Bihrle, 1999), up to larger species such as domestic turkeys *(Meleagris gallopavo)* (Roster, 1990), canada goose *(Branta canadensis)* (Anderson & Roetker, 1978; Anderson & Sanderson, 1979), and roe deer *(Capreolus capreolus* (Strandgaard, 1993). The studies have either tested the effects of a single shot type, or compared shot types against each other. The most common materials tested against each other have been steel and lead, based on the assumption that if material density is an important factor affecting killing efficiency, steel and lead represents the extremes (Pierce et al., 2015). Results from the comparative studies vary. Some studies found that lead performs better than steel (Hebert et al., 1984; Kozicky & Madson, 1973); one indicated that steel can perform better than lead (Anderson & Sanderson, 1979), but many find no significant difference between the two shot types (Anderson & Roetker, 1978; Andrews & Longcore, 1969; Humburg et al., 1982; Mikula et al., 1977; Nicklaus, 1976; Pierce et al., 2015; Smith & Roster, 1979; Strandgaard, 1993).

Norwegian regulations on lead shot use began with a ban on lead shot for wetland hunting in 1991 (Miljødirektoratet, 2014). Lead shot was banned on Norwegian shooting ranges in 2002, and in 2005 a total ban against all lead shot use was introduced. In 2015 the ban was eased, and lead was allowed for hunting a number of specific species. This was the result of a political process, where the Norwegian Association of Hunters and Anglers (NJFF) and other interest organizations had been lobbying for lifting the ban over a number of years. The scientific advisory institutions involved in the political hearing leaned on current international science to argument for continuation of the existing ban. Scientific advice was described by many politicians as too complicated and too contradictory to be clearly understood, and the majority of political parties gave their votes in the direction of the interest organizations asking for an ease on the ban (Arnemo et al., 2016). One of the main arguments politicians who voted for easing the ban focused on, was humane and ethical killing of game. It was claimed that animal suffering would increase as a result of replacing lead with non-toxic shot, and that lead was the shot type that provided the quickest and most efficient killing of game (Stortinget, 2015). In October 2017 the Norwegian Environment Agency announced that a new EU-proposal for union wide regulations on lead shot might affect future Norwegian regulations on the matter, as Norway is committed to EU-regulations through the EEA agreement. The final decision over the new EU-regulations is expected in 2019 (Miljødirektoratet, 2017).

In the years 2003-2006 the Norwegian Hunters and Anglers Association (NJFF) conducted their own investigation on the killing efficiency of different shot types. This project, called the Test hunter project, collected field reports from voluntary hunters using a large variety of shot types on a variety of species. The possibilities of new regulations on shot types, and the differing results from previous studies, gives cause to examine the data collected by NJFF. The fact that these data were collected by hunters and their own interest organization provides an opportunity for finding facts that should have credibility also in the hunting community. The data might provide insight into how the different shot types performs, both in light of crippling rates affecting population mortality rates, but also how different shot types may cause animal suffering when shooting game. As the Norwegian lead shot ban is still in effect on many species, a better understanding of the non-toxic substitutes will still have value if Norwegian law is not largely affected by the proposed EU- regulations.

To investigate performance of lead shot and the non-toxic alternatives used in the Test hunter project, two research questions were asked:

1: How do the different shot types and pellet sizes perform in regard to bagging probability and light hit probability?

2: If performance differs between pellet sizes of each shot type, how do the most efficient pellet sizes in regard to high bagging probability and low light hit probability compare between shot types?

Based on the results, the goal was to give recommendations about:

-Which pellet size of each shot type should hunters use to minimize crippling loss by maximizing numbers of bagged birds per hit.

-Which pellet sizes of each shot type should hunters use to minimize animal suffering regardless of bag rate.

-How should hunters adapt their maximum shooting range with specific shot types and pellet sizes.

2 Materials and Methods

Data collection

The data used in this study was gathered by the Norwegian Hunters and Anglers Association during the hunting seasons of 2002/2003, 2003/2004, and 2004/2005. Data collection was done by approximately 100 voluntary hunters recruited through an advertisement in the association's membership publication. To represent the varied group of Norwegian hunters, volunteers were selected based on where they lived, their age, experience as hunters, and which species they hunted. Young or inexperienced hunters were excluded from the group to make sure all participants had solid hunting experience. This was based on the assumption that interpretation of game reactions would be more accurate among the more experienced hunters. Both volunteers with and without NJFF membership were included among the test hunters. Hunters who failed to report correctly the first season were replaced by other hunters the following seasons.

Approximately 100 cartridges were distributed to each hunter every year of the study period. The cartridges were donated by three importers, retailers and distributors of hunting ammunition in Norway (see appendix, table 1). Cartridges were distributed to hunters based on their guns and species hunted. All hunters were given all distributed shot types over the three hunting seasons. Matching of ammunition to the specific hunting situation was done by the hunters themselves, and they knew which type of ammunition they were using. Because some hunters also used their own personally bought ammunition in addition to the distributed cartridges, the data contains records on several other types of ammunition than what was originally distributed.

Report forms and instructions on how to fill these in were sent to all participants. The report form required hunters to enter information about species, cartridge name, pellet size in US size, shot type, shot distance, shot angle, reaction to shot, whether the game fired at was bagged (i.e., found or lost). All hunting situations where game was hit were recorded. If an encounter with game resulted in only missed shots, no records were made (Rindal, 2017 pers. comm.). The results were recorded from the start of the hunting seasons for the various game species, up to the 15th of April next year.

Data material

The data set contained info on a large selection of species. The observations registered as ptarmigan includes the two species willow ptarmigan *(Lagopus lagopus)* and rock ptarmigan

(Lagopus muta). Ptarmigan stood out as the species in the data set with enough observations to perform robust statistical analysis on a wide selection of shot types and pellet sizes. Because of strong imbalance between shot types and pellet sizes, or low number of observations, other species in the data set were not used in analysis (see appendix, table 2, for a complete list of species).

The variables in the data set used for analysis were chosen because they were assumed to be relevant for analyzing shot type performance, or because they have been identified as relevant by previous studies or on the topic. Variables used in this study were:
-Hunter. The variable is used based on the assumption that individual hunters may vary in their hunting and observation skills.
-Pellet size, recorded in US sizes. Pellet size is used in analysis because it has been identified by previous research as a factor that can affect killing efficiency (Anderson & Sanderson, 1979; Kozicky & Madson, 1973; Strandgaard, 1993).
-Shot type, defined as the material the shot in a cartridge is made of. The shot types used for testing are steel, bismuth and lead, which were the shot types in the data set with enough observations for statistical analysis. Steel and lead are commonly tested in other studies on the subject of shot type performance. Lead represents the accepted standard and steel represents the extreme deviant in term of material density, which means that effect differences caused by density differences are likely to be detected when these are tested against each other (Pierce et al., 2015).
-Shot Angle, represented with three categories: Front, Rear, and Side. All shots fired at angles above 45degrees are recorded as side. Angle was included because it can affect how well hits are placed when hunters shoot birds, as side shots may be more difficult for the hunters (Bihrle, 1999). The sample size of frontal shots in the data set is low, and was therefore combined with rear shots in the analysis, resulting in two categories: Front/Rear and Side. This was done on the assumption that differences in hitting capabilities between side shots and frontal/rear shots are more important for the effects of hits, than possible differences in vulnerability from frontal and rear shots on birds of the relatively small size of Ptarmigan.
-Distance, recorded in meters. Distance was included because previous research show that increased distance can have a negative effect on bag rates (Cochrane, 1976; Hebert et al., 1984; Pierce et al., 2015; Smith & Roster, 1979). Distance was estimated without laser rangefinder or measuring tape, and in practice most often rounded to the closest 5 meter.
-Game found, recorded as yes or no.

-Response, recorded in four different categories, as observed by the hunter as reaction to fired shots: M: Miss, no observed reaction in game from the fired shot. HC: Hit Comprehensive, a heavy, but not killing hit. HL: Hit Light, hit but still flying, or running with light injuries. HD: Hit Dead, dead when hit, or dead within two minutes after hit. Response was only recorded for situations including at least one hit. If neither first nor second shot hit, resulting in a double miss, no record was made.

Variables created or modified for this study

To create models for predicting how different shot types and pellet sizes perform in light of the research questions, two new response variables and one predictor variable were created using the existing data.

The new variable "Bagged" was created for predicting the probability of bagging a bird when a hunter reports a hit. The variable was calculated from the variables "response" and "game found". All misses, and all hits that were affected by previous hits on the same bird where removed. Four hits that had response recorded as "Hit Dead" (HD), but were not registered as found, were also removed. This new variable is a binomial 0/1 variable, where "1" means game hit with a single shot and found by the hunter, and "0" means game hit with a single shot but not found. "Bagged" then becomes a measure of how many birds are actually found by the hunter as the result of a single hit.

To enable predicting how the various shot types and pellet sizes perform in regard to lightly wounding hit birds, a new variable was created by modifying the variable "Response". Misses were removed, and "Hit Light" was set as "1" while HD and HC were set as "0". This new variable was named "Light Hit", and is a binomial 1/0 variable, where "1" means Hit Light, and "0" means Hit Dead or Hit Comprehensive.

To enable quantification of differences across shot types, the variables "shot type" and "pellet size" were merged into a new variable called "size_type", for example US size 5_steel.

Data sub-setting

The recorded distances varied from 1 to 95 meters. The main bulk of observations were recorded from 15 to 35 meters, with 7 % below and 7.5 % of observations above this interval. Observations outside the 15 to 35 meter interval were excluded, as number of observations for each shot type and pellet size was very low at these ranges, and because the few observations at longer ranges could have a disproportionate influence on the results. Observations over 35 meters do also largely exceed the Norwegian Hunters and Anglers Associations maximum recommended shotgun shooting range of 30 meters (NJFF, 2016). Observations that were affected by more than one hit on the same bird were excluded. Thus, all included observations are the result of either one single shot hitting a bird, or a second shot resulting in a hit after a miss had been fired. Observations were removed if they lacked entries for any of the used variables. Shot types and pellet sizes were included if sample sizes were large enough for models to converge. The shot types and pellet sizes remaining for analysis after sub setting are shown in table 1.

Table 1: Observations used for analysis. Shows number of each shot type and pellet size for both the Bagged and Light hit variable remaining after sub-setting.

Shot type	Pellet size	Bagged	Light hit
Lead	5	38	38
Lead	6	71	71
Lead	7	94	95
Steel	2	45	45
Steel	4	168	168
Steel	5	103	103
Steel	6	328	328
Bismuth	7	298	300
All	-	1145	1148

Statistics/analysis

Statistical analyses were performed in R, version 3.3.3 (R Core Team, 2017). Based on the a priori assumption that the effect of distance on killing efficiency may be non-linear, Generalized Additive Mixed Models (GAMM) were created using the Gamm4 package in R (Wood & Scheipl, 2017). Model selection and significance testing of predictor variables for all models was done by likelihood ratio testing. Likelihood ratio testing compares how likely the existing data is to occur under two compared models, where one is nested within the other (Pinheiro & Bates, 2000).Although GAMM were used for all final models, linear models were used to examine possible interactions between the variables pellet size and distance. Because interactions are easier to test in linear models, a GLMER model created with the lme4 package was used for this testing (Bates et al., 2015).As inclusion of interaction between distance and pellet size was never supported in any of the models for bagging or light hit probability (LRT: p always >0.05), interactions were excluded from further analyses. The GAMM analyses revealed that effects of distance were linear or close to linear in all cases. GAMM models were still used for analysis, as the Gamm4 modeling package both handles linear effects and permits creating confidence intervals for predicted values, unlike the package for linear mixed models (lmer4).

A common method for comparing shot shell performance is to measure numbers of bagged, lost, wounded or crippled birds per recorded hit. Because double-misses were not reported by hunters, no per-shot rates could be calculated from the data. Thus, the per-hit measure was the only option for this study.

Response variables used in the models were Light Hit and Bagged. As these are binomial variables, family was set as binomial with logit link in the models. The predictor variables used in the tested models were pellet size (factor variable with up to X levels), shot angle (factor variable with two levels), and distance (continuous variable fitted as spline). Predictor variables remaining after model selection were pellet size and distance, as effects of shot angle was found to be non-significant on all tested shot types (LRT: p always >0.05). To avoid possible pseudo replication effects caused by varying shooting abilities between hunters, hunter was included as random intercept in all models.

Due to the strong unbalance between shot type and pellet size (table 1), analysis of effects of distance and pellet size were done in one step, and comparison of the different shot types were done in a second step. The first step consisted of separate models run for each shot type. This was done to ensure the estimated effects of distance on each individual shot type were not influenced by data on other shot types. In the second step, all shot types and pellet sizes were compared in a common model. The aim of this second step was to evaluate if all shot types have equally good alternatives, and if there are significant differences between the best performing shot sizes for each shot type. For this testing, two GAMM models were created, with the response variables Bagged and Light hit. In these models the predictor variable pellet size was changed for the variable size_type.

3 Results

Effects of distance and pellet sizes on bagging probability

For steel shot, the probability of bagging hit birds decreased with increased shooting distance ($p < 0.001$; Fig. 1&2). The negative effect of distance tended to be stronger for the small compared to large pellet sizes ($p = 0.068$; Fig. 1). The probability of bagging birds dropped from 0.95 at 15m, to 0.71 at 35m for the smallest steel shot (US size 6), but showed virtually no drop (0.99 to 0.95) for the largest steel shot (US size 2) (Fig 1). Lead shot showed a high predicted bagging probability at all ranges, and the negative effect of distance on bagging probability of lead shot was non-significant ($p = 0.0978$; Fig 1&2). There was no clear difference in effect between pellet sizes over the relatively narrow size range of lead shot tested (size range 5-7; Fig. 1). Predictions for all pellet sizes of lead shot were between 0.99 to 0.90 birds bagged per hit for the entire range of distances (Fig 2). The model for Bismuth shot showed no effect of distance on the probability bagging birds (Fig. 2). As only one pellet size of Bismuth shot (US size 7) was available, the effect of pellet size could not be tested.

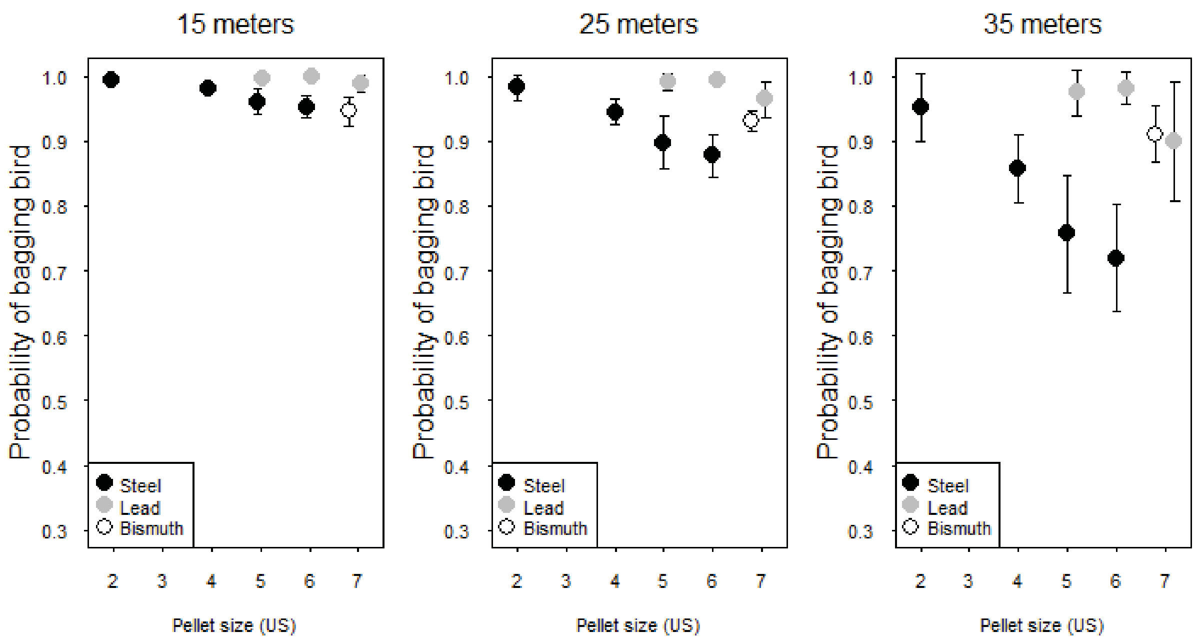

Fig. 1: Effect of pellet sizes on bagging probability (predicted probability of bagging the bird when a hunter reports hit) at ranges of 15, 25 and 35 meters. Predictions are from three models with effects of distance and pellet size each shot type. Error bars show +/- one standard error.

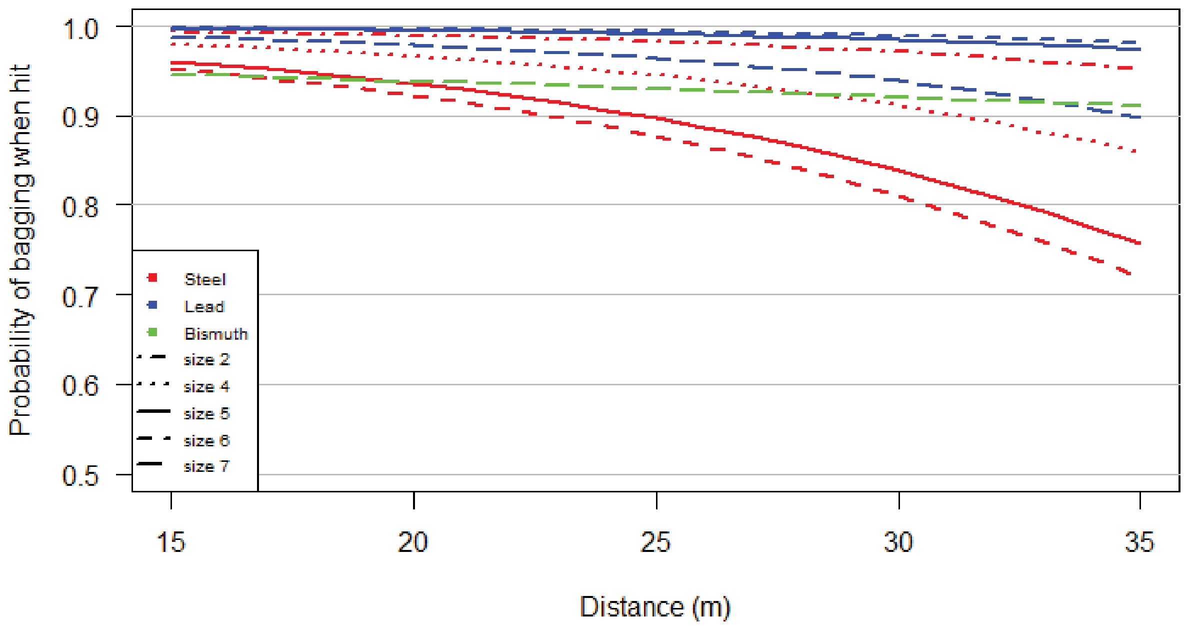

Fig. 2: Changes in bagging probability (predicted probability of bagging the bird when a hunter reports hit) over a range of 15 to 35 meters, shown for the analyzed shot types and pellet sizes. Predictions are from three models with effects of distance and pellet size for each shot type.

Effects of distance and pellet size on light hit probability

The results for probability of light hit were largely inverse of the bagging probability results. The probability of light hits increased with range for steel shot ($p<0.001$; Fig. 3&4). Although only a weak tendency, the effects of distance were somewhat stronger for small compared to large pellet sizes ($p=0.129$; Fig. 3). The probability of light hits increased from 0.20 at 15m, to 0.49 at 35m for the smallest steel shot (US size 6), and also showed increase (0.10 to 0.32) for the largest steel shot (US size 2) (Fig. 3). Lead shot showed low probability of light hit at all ranges, and the slight increase in light hit probability with increasing distance was non-significant ($p=0.114$, Fig. 3&4). There was no clear effect difference between pellet sizes (size range 5-7) of lead shot (Fig. 3). Predictions for all pellet sizes of lead shot were between 0.01 to 0.18 light hits per hit for the entire range of distances (Fig 4). The model for bismuth shot showed no effect of distance on probability of light hits (Fig. 4). As bismuth was only represented with one pellet size (US size 7), effects of pellet size could not be tested.

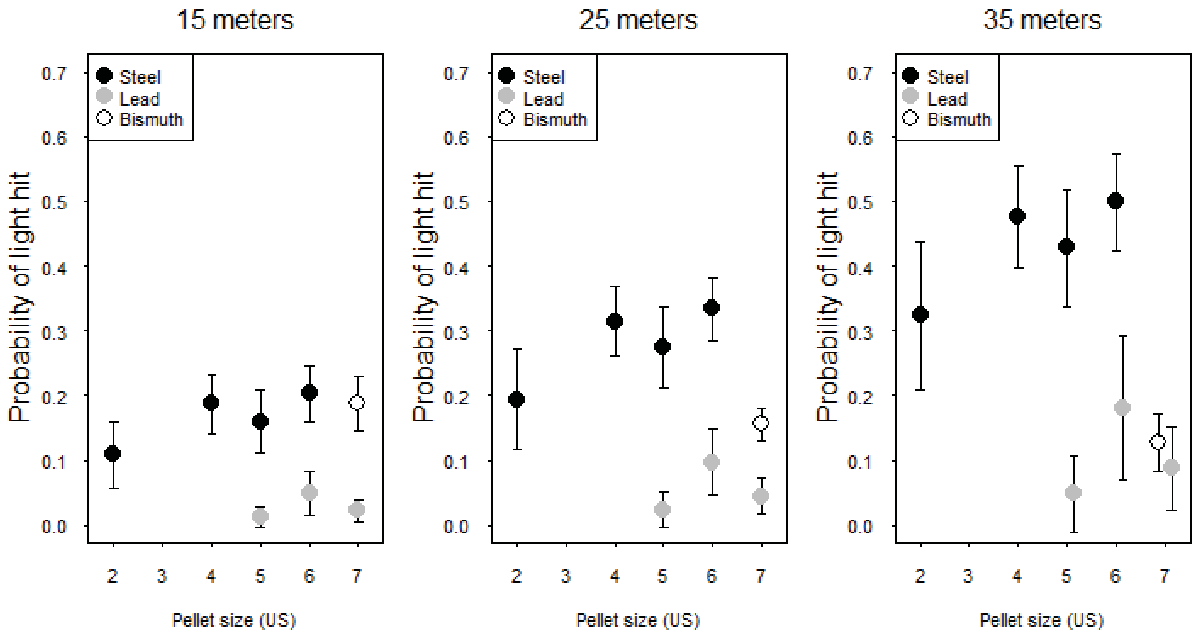

Fig. 3: Shows effect of pellet sizes on predicted probability of light hit when a hunter reports a hit at ranges of 15, 25 and 35 meters. Predictions are from three models with effects of distance and pellet size for each shot type. Error bars show +/- one standard error.

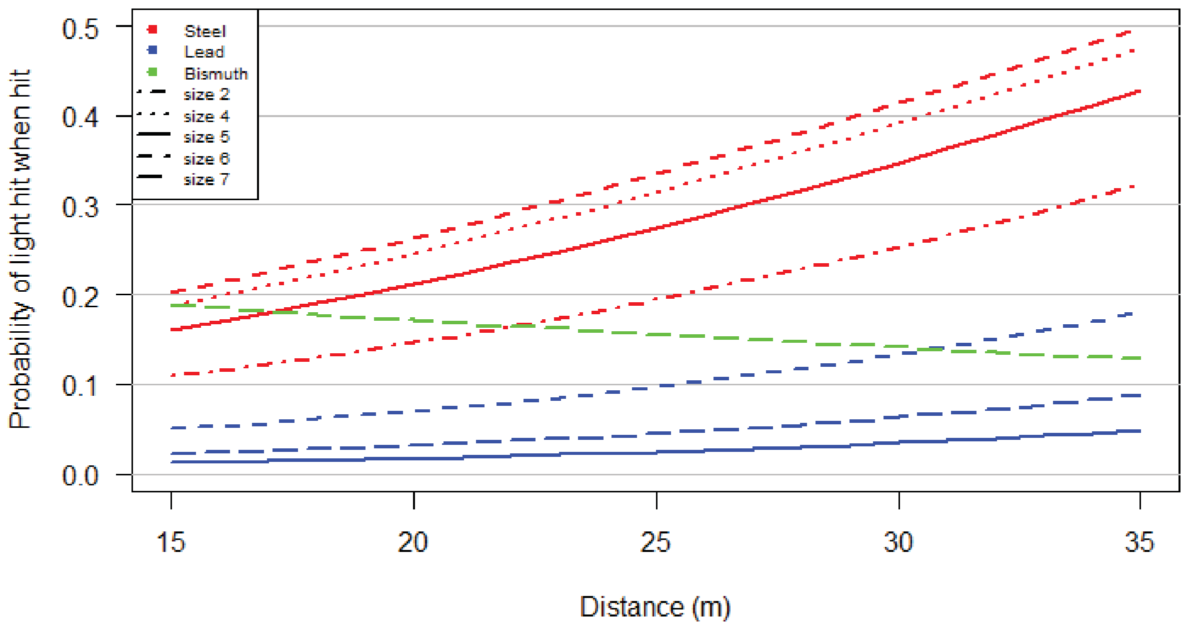

Fig. 4: Changes in probability of light hit (predicted probability of report of light hit when a hunter reports hit) over a range of 15 to 35 meters, shown for the analyzed shot types and pellet sizes. Predictions are from three models with effects of distance and pellet size each shot type.

Comparison of bagging probabilities between shot types and pellet sizes

The next step was to compare bagging probability between all pellet sizes and shot types. As lead shot of US size 6 had shown the highest predicted effect on bagging birds of all pellet sizes and shot types in previous analysis, size_type lead 6 was set as the reference level for comparison. The shot types and pellet sizes that proved significantly different in bagging probability from Lead size 6 ($p < 0.05$) were steel sizes 4, 5 and 6 (Table 2). Lead sizes 5 and 7, steel size 2 and bismuth size 7 showed no significant difference from lead size 6 ($p > 0.05$; Table 2).

Table 2: Summary from GAMM model of effects of all shot types, pellet sizes and distance on bagging. All shot types and pellet sizes are represented by the variable size_type. The reference level for the effect of shot type and pellet size is lead US size 6.

Variable	Estimate	SE	Z	P
Intercept	5.29	1.08	4.89	< 0.001
Lead size 5	-0.29	1.47	-0.19	0.843
Lead size 7	-1.82	1.14	-1.58	0.112
Steel size 2	-1.34	1.51	-0.88	0.377
Steel size 4	-2.55	1.08	-2.35	0.018
Steel size 5	-3.31	1.12	-2.95	0.003
Steel size 6	-3.36	1.06	-3.14	0.002
Bismuth size 7	-1.88	1.08	-1.72	0.082

Comparison of shot types and pellet sizes on their probabilities of light hit

As lead shot of US size 5 had shown the lowest predicted probability of light hits of all pellet sizes and shot types in previous analysis, size_type lead 5 was set as the reference level for comparing effect sizes. The shot types and pellet sizes that proved significantly different in light hit probability from lead size 5 ($p < 0.05$) were steel sizes 4, 5 and 6 (Table 3). Steel size 2 tended toward significant difference from lead size 6 ($p = 0.063$; table 3). Lead sizes 5 and 7, and bismuth size 7 showed no significant difference from lead size 6 (albeit tendencies for lead and bismuth size 7 to perform poorer; Table 3).

Table 3: Summary from GAMM model of effects of all shot types, pellet sizes and distance on light hit. All shot types and pellet sizes are represented by the variable size_type. The reference level for the effect of shot type and size is lead of size 5. pellet size is lead US size 6.

Variable	Estimate	SE	Z	P
Intercept	-3.54	1.05	-3.36	< 0.001
Lead size 6	1.49	1.10	1.36	0.173
Lead size 7	0.96	1.10	0.87	0.382
Steel size 2	2.11	1.14	1.85	0.063
Steel size 4	2.84	1.06	2.68	0.007
Steel size 5	2.68	1.08	2.48	0.013
Steel size 6	2.81	1.05	2.67	0.007
Bismuth size 7	1.65	1.06	1.56	0.119

4 Discussion

Selection of non-toxic alternatives to lead shot is still a debated topic internationally as well as in Norway. This study found that bismuth shot performs equally to lead, and that large steel shot perform well in a bagging perspective, but might cause increased rates of lightly wounded game. The decline in ptarmigan populations over the recent 10-15 years have put both Willow- and Rock ptarmigan as Near Threatened (NT) on the Norwegian Red List for species (Kålås, 2015). This necessitates knowledge of how shot types differ in wounding and bagging hit birds.

The findings of this study show the importance of correct pellet selection when using steel shot for hunting. They also suggest that an even larger pellet size of steel shot than traditionally recommended may be necessary to maintain high bag rates. However, the results indicate that large steel shot may increase animal suffering regardless of bag rates, because more birds are wounded before eventually retrieved by the hunter. Norwegian ptarmigan hunters often use pointing dogs, who also aid retrieval of wounded birds. This may explain why bagging probabilities of large steel shot are not directly inverse to light hit probabilities. Hunters using the smaller pellet sizes of steel shot will have a higher rate of un-retrieved birds if they do not restrict their shooting distances. If wildlife managers use bag limits to reduce hunting mortality, a switch to ammunition that causes reduced bag rates can increase the total population mortality caused by hunting.

Bagging probabilities for the tested shot types

When the correct pellet size is selected, lead, steel, and bismuth shot gives similar performance in regard to probability of bagging birds. The model comparing effects of all pellet sizes and shot types also supports this view; there are no significant differences in bagging probability when Steel shot of US size 2 and Bismuth shot of US size 7 is compared against Lead shot of US size 6. These findings corresponds with many previous studies who have tested selected loads of steel and lead shot against each other; with correct pellet size and load selection, steel and lead shot give similar rates of bagged or crippled game (Anderson & Sanderson, 1979; Andrews & Longcore, 1969; Humburg et al., 1982; Mikula et al., 1977; Nicklaus, 1976; Pierce et al., 2015; Roster, 1990; Smith & Roster, 1979). Bismuth shot has not been studied as extensively as steel and lead, but bismuths' relative softness and higher density means it has good potential for similar performance as lead shot (Lowry, 1993). This study supports this claim; the tested bismuth shot is similar to lead in bagged birds per hit at all ranges tested.

The lower bagging probability of steel shot compared to lead shot of similar pellet sizes in this study, corresponds with the traditional understanding of the limitations of steel shot. Steel is lighter than lead, which necessitates pellets of larger size than lead to retain enough energy to penetrate game adequately at longer ranges (Brister, 2014, p. 295; Krüper, 1992). Pellet sizes recommended for ptarmigan hunting by the Norwegian Association of Hunters and Anglers is lead shot of US size 6-7 and steel shot of US size 4-5 (NJFF, 2016). Predictions from the steel shot model in this study indicate that even larger shot than previously recommended should be used to maintain high bagging probability. If small pellet sizes of steel shot are used, shooting distances must be reduced. To maintain an expected bag rate of 0.90 per hit, hunters using smaller shot than US size 2 should limit their shooting distances to 30 meters for US size 4, to 24 meters for US size 5, and to 22 meters for US size 6. A study that may support this finding is the CONSEP pheasant test of 1997-98. This study compared the effects of a broad selection of pellet sizes of steel shot for bagging ring-necked pheasants. They found US 2 as the most efficient pellet size (Bihrle, 1999). Pheasants are larger than ptarmigan, but the traditionally recommended lead pellet sizes for pheasant hunting are similar to the ones recommended for ptarmigan (BASC, 2018).

But why do the model findings on steel shot pellet size for good bagging performance differ from traditionally recommended pellet size? The CONSEP pheasant tests indicated that the very long tail feathers of pheasants creates a "balling effect", where the hair-like feathers wrapped around pellets and reduced penetration. Selected loads of US size 4 steel shot has shown effects close to lead shot on wild and domestic ducks in several previous studies (Andrews & Longcore, 1969; Humburg et al., 1982; Mikula et al., 1977; Nicklaus, 1976). As ptarmigan do not have the long tail feathers of pheasants, feather penetration problems is unlikely to be the reason why steel shot of US size 4 does not perform effectively in this study's models. An explanation for this could be cartridge selection. The data set does not contain info on load weights or velocity of the distributed cartridges or cartridges supplemented by the test hunters. Velocity affects penetration, and load weights affect pattern density, two factors of great importance for efficient performance on game (Pierce et al., 2015). If the tested cartridges were selected by load weighs, pellet count and velocity, in an attempt to maximize performance for each shot type and pellet size, steel shot of US size 4 might have performed better than shown in this study's models.

Light hit probabilities for the tested shot types

Large steel shot showed its potential for equal performance with lead shot in the analysis for bagging probability. If light hit probabilities were directly inverse of bagging probabilities, large steel shot would perform equally well with regards to light hits too. However, this is not the case, as the rate of light hits with US size 2 steel shot compared unfavorably with lead and bismuth shot. This is unlikely to be caused by lacking penetration, as the aforementioned necropsy analysis of pheasants and similar analysis on roe deer has shown this size of steel shot to have good penetrative abilities (Bihrle, 1999; Strandgaard, 1993). There may be several explanations for the high rates of light hits with large steel shot. If penetration is sufficient, pattern density has been identified as an important factor for the efficiency of shotgun cartridges (Pierce et al., 2015).With an increase in pellet size, cartridges with the same load weight will contain less pellets (Brister, 2014 p. 299), which means that a cartridge loaded with large steel shot may not contain enough pellets to give the needed pattern density to give multiple pellet strikes on smaller game. This could explain why the rate of light hits is not inverse to the rate of bagged birds with US size 2 steel shot: low pattern density with the large pellets and lower pellet count wound birds without killing them fast, but instead cause less heavy hits. Norwegian ptarmigan hunting is often done with the help of pointing gun dogs, who also retrieve wounded or killed birds, and if many of the hunters in this study used dogs, it offers a reasonable explanation as to why the higher rates of light hits with large steel shot do not also show up as lower rates of bagged birds. However, the higher rates of light hits with steel shot also manifest themselves to some degree at closer ranges, where effects of low pattern density is unlikely to be relevant because the pattern has not spread out much yet. An explanation for this could be that effect differences between shot types at the closer ranges are caused by different pattern spreads. The relative hardness of different shot types affect how shot pellets are deformed in the gun barrel, and thereby how straight each pellet travels. The result of this is that a load of hard shot does not spread out its pattern as fast as a load of softer shot (Jones, 2010, p.132). A normal perception is that a tight pattern spread either hits or misses cleanly, but this is not entirely true. The tight patterns with less spread gives less margin for shooter error, but stray pellets at the edges of the pattern may still hit if a shot does not have enough forward allowance to center the main cluster of pellets on moving game. This way, a tight pattern spread of hard steel shot with a only a few shot at the edges of the pattern can give more crippling hits at close ranges than larger patterns of shot (Brister, 2014, p.129).

Penetration or misses, density or pellet hardness?

There is some controversy connected to the expected lower penetration caused by the relative low density of steel shot. The deformation that causes lead shot patterns to spread out faster than steel shot patterns will also give steel and lead shot different frictional air resistance. Deformed lead shot is therefore subjected to higher frictional air resistance than hard steel shot. The result is less difference in energy loss between the two shot types than some calculations suggests (Lowry, 1989; Roster, 1978). If this is correct, the margin for shooter error that lead shot gives over steel shot might be more important for bagging efficiency than shot density, at least at distances below 50 yards (46 meters) (Brister, 2014, p.302). As all data used in this study is from shots fired at 35 meters or closer, and if all pellet sizes of steel shot really have adequate penetrative abilities over the entire distance range, it could be argued that the lower margin for shooter error is the cause of the low performance of steel shot. The lack of significant differences in light hit probabilities between pellet sizes of steel shot may support this view. However, the bagging performance of steel shot was different between pellet sizes, especially at longer ranges. This supports the argument that steel shot of the smaller sizes do not have the penetrative abilities to bring birds down efficiently at long range. To sum up, both penetration and hitting may be relevant to explain steel shot performance in this study: the low margin for shooter error with steel shot could explain why light hit probabilities differ between shot types even at 15 meters, where penetration is unlikely to play a major role; and low penetrative abilities of small pellet sizes could explain why only large sizes of steel shot provide high bagging performance at longer ranges.

Shot angle

Shot angle is believed to be relevant for the hunters ability to place good hits on moving game, and for penetration to vital organs (Bihrle, 1999). Shot angle is also among the factors that have been shown to affect lethality when hunting roe deer with shotguns (Strandgaard, 1993). To explain why shot angle proved non-significant in this study, the hunted species and typical hunting situations may offer some explanations. As explained previously, the long tail feathers that cause penetrative problems in pheasants are not present on Ptarmigan. This could mean the effect of shot angle on pellet penetration to vital organs is reduced. The study that found shot angle to be of importance on roe deer was conducted with animals shot during driven hunting. This could mean that the animals move fast when shot at. When hunting Ptarmigan in Norway, birds are usually flushed, either by the hunter or by dogs. This means that the birds need some time to pick up speed, and the relatively slow moving accelerating birds might be easier to hit than driven game, reducing the significance of shot angle for hunters` ability to place good hits.

Do hunters need time for adaptation to new cartridges?

As previously argued, the tight pattern spreads of steel shot compared to lead, leads to difficulties in placing good hits on moving targets when using steel shot (Brister, 2014, p.295). This can be somewhat compensated for by switching chokes in hunting guns when using steel shot, but one can still speculate that velocity differences between shot types may cause an need for changes in forward allowance on moving game. Hunters who are accustomed to one type of ammunition may need some time to adapt to the new situation. An argument against this view is a French study that examined developments in hunter effectiveness after switching to non-toxic shot. No clear change in hunter effectiveness was found from 1995 to 2005, indicating that no adaption to new ammunition took place after switching from lead to non-toxic shot types (Mondain-Monval et al., 2015).

Study limitations

Some factors that are of importance when evaluating shot type differences are missing from the data set. Whether or not hunters used hunting dogs is not recorded. Use of dogs may influence how many lightly wounded birds are found and thereby classed as bagged. Load weight of cartridges is not recorded. Load weight directly influences the number of pellets in a cartridge, which again affects pattern density and number of pellets hitting game. Degree of choke used by hunters is not recorded, which in turn affects pattern spreads, and thereby might influence hitting abilities (Pierce et al., 2015). As misses were not recorded if they did not occur together with a shot that hit, no good hit/miss rates can be calculated. While recording misses are not of direct importance for analyzing the effects of hits, they are obviously essential when analyzing the probability of hits, and could perhaps provide insights on a possible relationship between hit rates and types of hit.

Unfortunately, lead and bismuth shot were not represented with a large selection of pellet sizes in this study. This excludes the possibility of analysis for effects of a wide selection of pellets sizes on these two shot types. Lead shot has been in use over very long time, so the represented sizes may reflect the most efficient sizes for lead shot. Analysis of a wider selection of pellet sizes of bismuth shot could possibly have provided new knowledge on pellet selection for this shot type.

Possible sources of errors or inaccuracy

The fact that the hunters knew which shot type and pellet size they were using introduces a possible source of bias in this study, Hunters' and independent observers recognition of hits and misses has been shown to correspond accurately (Pierce et al., 2015), but observations of categories of hits might be less accurate. In the 1979 Tulelake study, comparison was made of hunter comments and observer reports of shot type performance. Shot types in use were not known by hunters or observers, but it was found that hunters' opinions of shot types significantly affected their comments on performance when they believed to know what shot type they were using (Smith & Roster, 1979). This means that hunters with a prejudice towards a specific shot type may be inclined to report poorer on this shot type, and thereby create a bias against or in favor of specific shot types. If this bias exists in the data set, it will affect hit categorizations in the "Response" variable, and thereby bias the light hit models in the direction of hunters opinions. However, the yes/no registrations of the "Game found" variable will not be affected, and the models of bagging probability will not be biased.

Distance estimation errors have been detected in previous studies; hunters tend to overestimate when shooting at shorter ranges and underestimate at very long ranges. (Humburg et al., 1982; Pierce et al., 2015; Smith & Roster, 1979). As this study does not include observations at the very long ranges often tested in American studies, the relevant estimation error is that of overestimating shots at shorter ranges. This would mean that reports of well performing shots at the longer ranges in the data set could actually have been fired at closer range than reported. However, distance errors are expected to be the same for all ammunition types and will not affect the comparisons made in this study.

As cartridges were distributed in both 20 gauge and 12 gauge, shotguns in both gauges were used by hunters who reported their observations, but observations in the data set do not include information of gauge. Shotgun gauge is likely to affect pattern spread (Jones, 2010, pp.154-158), which in turn could affect hit rates and wounding rates (Brister, 2014, pp.129-133), thereby biasing the results if one gauge has been used more with a specific shot type than the other gauge. However, this is expected to just introduce unexplained noise and no error in the comparisons between ammunition types.

The merging of front and rear shots in the variable shot angle makes sense from the perspective of hitting capabilities, but may introduce an error source from an anatomic vulnerability perspective. The gizzard of birds digestive system offers a tough penetration barrier which could stop pellets from rear shots reaching vitals such as heart or lungs (Bihrle, 1999). If this is the case, this would mean that categories of the “Response” variable could differ between frontal and rear shots, and thereby affect the results in the light hit model. It could also interfere with the significance of shot angle in the models. As the reason for merging was a very low sample size of frontal shots, this is very unlikely to have affected the conclusions of the study.

The data used in this study is probably influenced by how hunter behavior and choices affect killing efficiency for the different shot types. This means that the data may not be an objective measure of how a well composed cartridge adapted for a specific hunting situation may perform, but rather a measure of how hunters perform with the different shot type as a result of their individual choices and judgments. However, the knowledge of how hunters’ perform with the different shot types under field conditions provided by this study should be of great importance, as hunter choices affect what happens in real life hunting situations.

5 Conclusion

Returning to the stated research questions, the models provide some answers:

Performance of different shot types and pellet sizes in regard to bagging and light hit probabilities: Small sizes of steel shot have lower probability of bagging hit birds than large steel shot, bismuth shot and all sizes of lead shot. Large sizes of steel shot have a somewhat lower probability of causing light hits than smaller steel shot, but all lead and bismuth shot have even lower probabilities of causing light hits than steel shot.

Comparison between the best performing pellet sizes of each shot type: When comparing the pellet sizes that have the highest probability of bagging hit birds for each shot type, there is no difference in probability of bagging hit birds between lead and steel, or between lead and bismuth. When comparing pellet sizes that have the lowest probabilities of light hits for each shot type, there is no difference between probability of light hit between lead and bismuth, but a difference between lead and steel.

Suggestions for further research

Further research on the topic of shot type efficiency should aim at exploring effects of shot types in use that have not been extensively researched, such as heavy-shot, tungsten matrix. Future research should also ensure that all relevant pellet sizes for each shot type are included, and that load weights, shotgun gauges, and chokes in use are recorded. To avoid bias created by any prejudice against the tested shot types, it is important that neither observers nor hunters know what kind of shot type they are using or observing.

Implications of this study for hunters and wildlife management

To ensure a high bag rate at all ranges with the tested shot types and pellet sizes, steel shot of US size 2, lead shot of US size 5 and 6 should be used. Lead shot of US size 7 may provide similar results, but with some more uncertainty. Bismuth shot of US size 7 performs well, but other sizes were not tested.

To ensure the lowest amount of animal suffering regardless of bag rate, lead shot US size 5 and 7 or bismuth shot US size 7 should be preferred over all sizes of steel shot. Lead shot US size 6 may provide the same effect as other lead shot sizes, but with some uncertainty. If steel shot is used, US size 2 is preferred.

If hunters use steel shot without a conscious selection of pellet size, number of birds bagged per hit may decrease. If smaller pellet sizes of steel shot are used, shooting distances must be reduced. To maintain an expected bag rate of 0.90 per hit, hunters using smaller shot than US size 2 should keep their maximum shooting distances to 30 meters for US size 4, 24 meters for US size 5, and to 22 meters for US size 6. Use of small sizes of steel shot at longer distance could decrease numbers of bagged birds per hit from the 0.90 to the 0.70 range. If hunters are only restricted by bag limits, a decrease in bagged birds per hit can increase hunting mortality with negative consequences for population growth.

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Appendix

Appendix table 1: Cartridge types distributed to hunters by NJFF for testing

Importer	Cartridge name	Shot type	Gauge
Schou Våpen AS	Eley Bismuth Forest	Bismuth	12
Schou Våpen AS	Grand Prix Bismuth Forest	Bismuth	12 and 20
Schou Våpen AS	Schou Bismuth Forest	Bismuth	12
Schou Våpen AS	Kent Tunsten-Matrix	Tungsten	12 and 20
Gresvig AS	Gamebore Tungsten-Matrix	Tungsten	12
Gresvig AS	Clever Mirage Hevi-shot	Hevi-shot	12
Gresvig AS	Clever Mirage Steel-shot	Steel	12
Gresvig AS	Remington Hevi-shot	Hevi-shot	12 and 20
Magne Landrø AS	Rio Royal Steel	Steel	12

Appendix table 2: All species and number of observations registered in the data set

Species	Number of observations
Eurasian widgeon (*Anas Penelope)*	24
Pidgeon, species unspecified	192
Common snipe (*Gallinago gallinago*)	2
Common pheasant (*Phasianus colchicus*)	7
European badger (*Meles meles)*	3
Greylag goose (*Anser anser*)	154
European herring gull (*Larus argentatus*)	1
Mountain hare (*Lepus timidus*)	203
Long-tailed duck (*Clangula hyemalis*)	18
Hazel grouse (*Tetrastes bonasia*)	35
Canada goose (*Branta canadensis*)	35
Pink-footed goose (*Anser brachyrhynchus)*	5
Common teal (*Anas crecca*)	65
Hooded crow (*Corvus cornix*)	21
Common goldeneye (*Bucephala clangula*)	36
Goosander (Eurasian) (*Mergus merganser*)	2
European pine marten (*Martes martes*)	4
Eurasian jay (*Garrulus glandarius)*	5
Black grouse (*Tetrao tetrix*)	386
Grey partridge (*Perdix perdix*)	1
Common raven *(Corvus corax)*	11
Eurasian woodcock (*Scolopax rusticola*)	9
Red fox (*Vulpes vulpes*)	52
Redwing (*Turdus iliacus*)	1
Stoat (*Mustela erminea*)	4
Roe deer (*Capreolus capreolus*)	70
Red-breasted merganser (*Mergus serrator*)	48
Eurasian magpie or common magpie (*Pica pica*)	3
Mallard (*Anas platyrhynchos*)	245
Western capercaillie (*Tetrao urogallus)*	250
Great cormorant (*Phalacrocorax carbo*)	162
Gommon scoter (*Melanitta nigra*)	55
Great black-backed gull (*Larus marinus)*	5
European shag (*Phalacrocorax aristotelis*)	25
American mink (*Neovison vison*)	2
Common eider (*Somateria mollissima*)	287
Willow Ptarmigan (*Lagopus lagopus*) and Rock ptarmigan *(Lagopus muta)*	2436
NA	5

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